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Shao et al.

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(54) **PHOTOVOLTAIC DEVICE WITH A ZINC MAGNESIUM OXIDE WINDOW LAYER**

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(51) **Int. Cl.**

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H01L 31/0224	(2006.01)
H01L 31/073	(2012.01)
H01L 31/18	(2006.01)

(52) **U.S. Cl.**
CPC ***H01L 31/022466*** (2013.01); ***H01L 31/073*** (2013.01); ***H01L 31/1828*** (2013.01); *Y02E 10/543* (2013.01)

(58) **Field of Classification Search**
CPC H01L 31/022466; H01L 31/1828; H01L 31/073; Y02E 10/543
USPC 136/252, 260, 264, 265
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,160,678	A *	7/1979	Jain et al.	136/255
6,259,016	B1 *	7/2001	Negami et al.	136/265
2004/0182434	A1 *	9/2004	Hashimoto et al.	136/256
2008/0115827	A1 *	5/2008	Woods et al.	136/255
2009/0020149	A1 *	1/2009	Woods et al.	136/244
2009/0084438	A1 *	4/2009	den Boer et al.	136/256

(Continued)

FOREIGN PATENT DOCUMENTS

CN	1531114	9/2004
DE	10 2007 047 146 A1	4/2008

OTHER PUBLICATIONS

English Machine translation of DE102007047146A1.*

(Continued)

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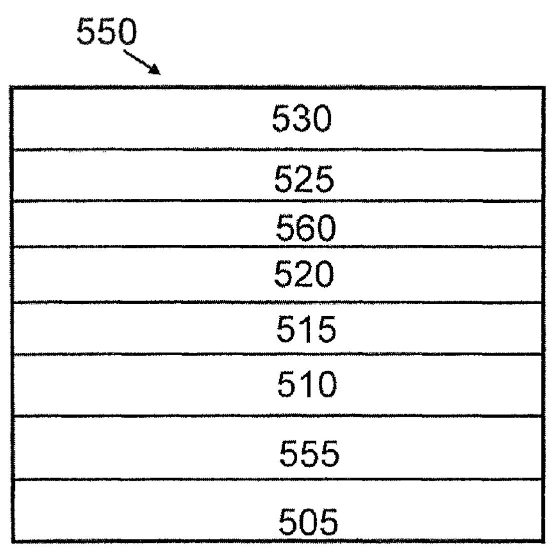
(57) **ABSTRACT**

Methods and devices are described for a photovoltaic device and substrate structure. In one embodiment, a photovoltaic device includes a substrate structure and a CdTe absorber layer, the substrate structure including a $Zn_{1-x}Mg_xO$ window layer and a low conductivity buffer layer. Another embodiment is directed to a process for manufacturing a photovoltaic device including forming a $Zn_{1-x}Mg_xO$ window layer over a substrate by at least one of sputtering, evaporation deposition, CVD, chemical bath deposition process and vapor transport deposition process. The process including forming a CdTe absorber layer above the $Zn_{1-x}Mg_xO$ window layer.

9 Claims, 7 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

2011/0005591	A1	1/2011	Buller et al.
2011/0005594	A1	1/2011	Powell et al.

OTHER PUBLICATIONS

A. Morales-Acevedo, "Thin Film CdS/CdTe Solar Cells: Research Perspectives," Solar Energy, vol. 80, pp. 675-681, (2006).

N, Naghavi et al., "Buffer Layers and Transparent Conducting Oxides for Chalcopyrite $Cu(In,Ga)(S,Se)_2$ Based Thin Film Photovoltaics: Present Status and Current Developments," Progress in Photovoltaics: Research and Applications, vol. 18, pp. 411-433, 2010.

J. Sites et al., "Strategies to Increase CdTe Solar-Cell Voltage," Thin Solid Films, vol. 515, pp. 6099-6102, 2007.

J. Perrenoud et al., "Application of $ZnO_{1-x}S_x$ as Window Layer in Cadmium Telluride Solar Cells," 2010 35th IEEE Photovoltaic Specialists Conference , pp. 000995-001000, Jun. 1, 2010. ISBN: 978-1-4244-5892-9/10.

Takashi Minemoto, "$Cu(In,Ga)Se_2$ solar cells with controlled conduction band offset of window/$Cu(In,Ga)Se_2$ layers", Journal of Applied Physics, Jun. 15, 2001, pp. 8327-8330, vol. 89, No. 12.

Takashi Minemoto et al., "Control of conduction band ofset in wide-gap $Cu(In,Ga)Se_2$ solar cells", Solar Enerygy Materials & Solar Cells, 2003, pp. 121-126, vol. 75.

M. Gloeckler, et al., "Efficiency limitations for wide-band-gap chalcopyrite solar cells", Thin Solid Films 480-481 (205) p. 241-245.

* cited by examiner

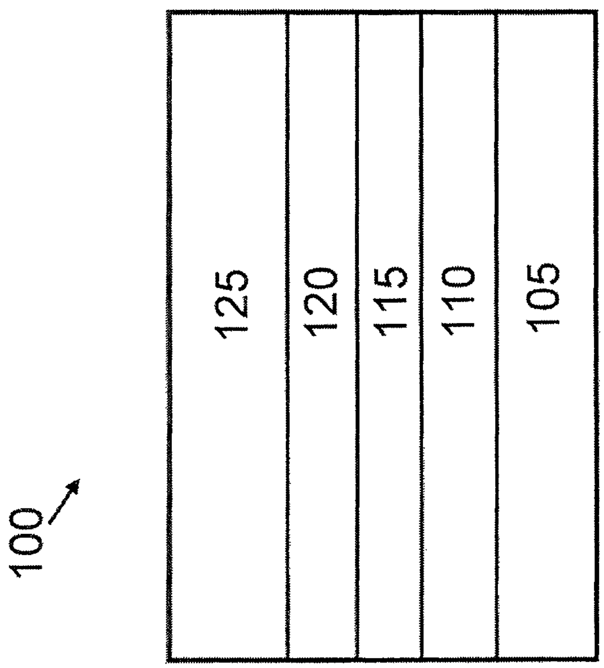


FIG. 1
-BACKGROUND-

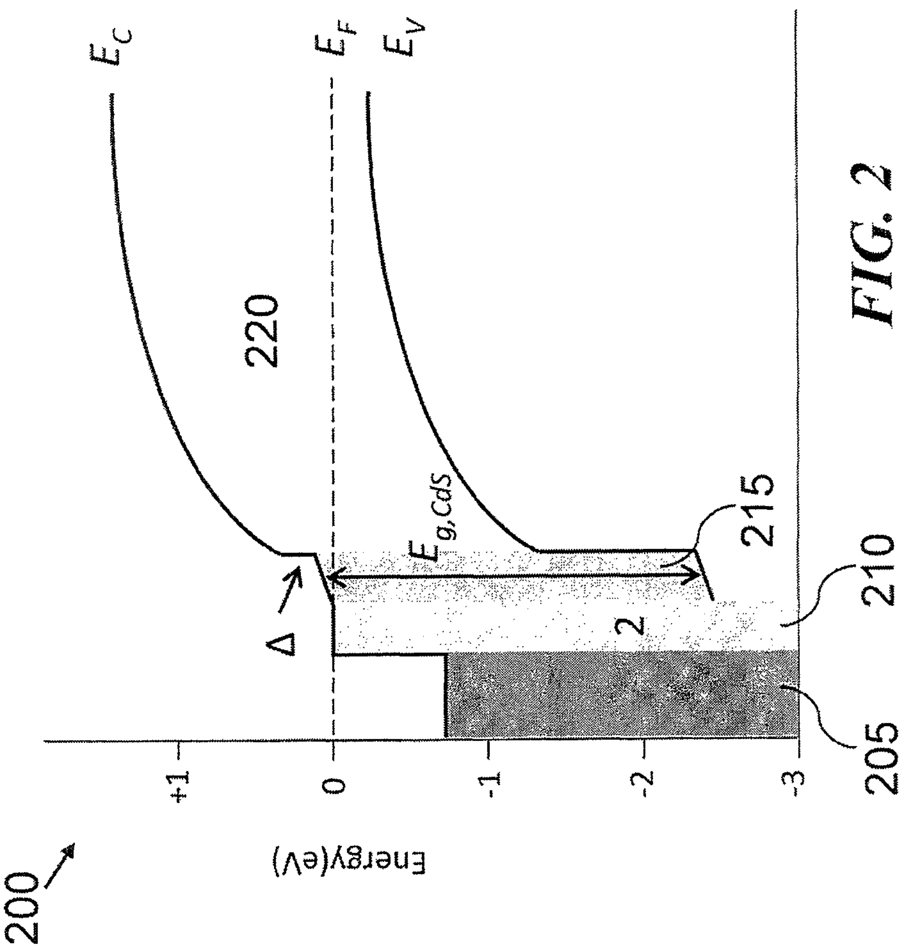


FIG. 2
-BACKGROUND-

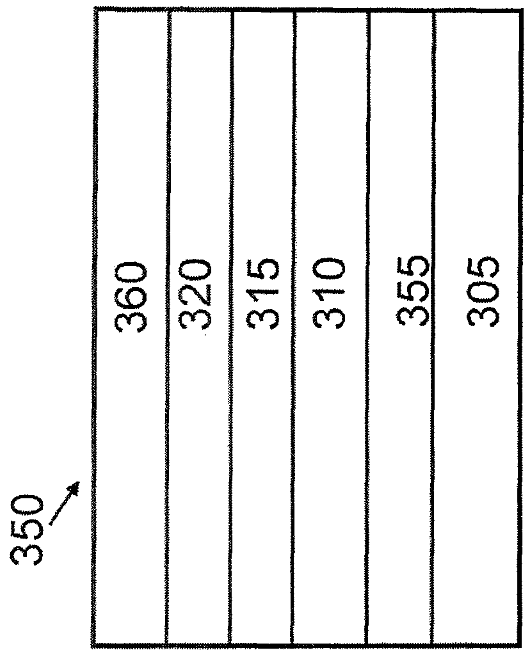


FIG. 3B

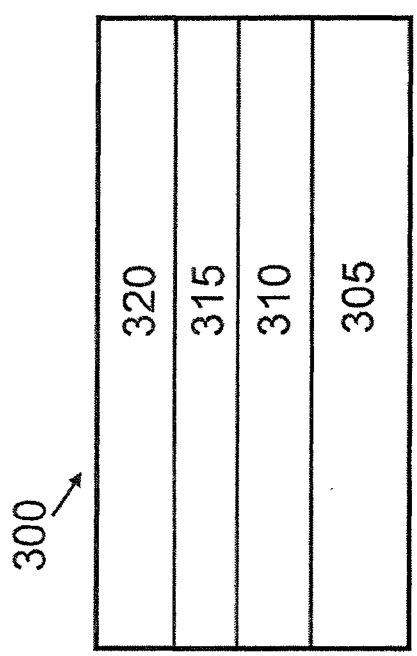


FIG. 3A

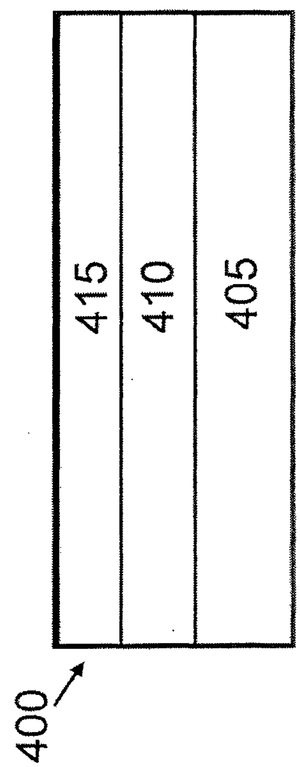


FIG. 4

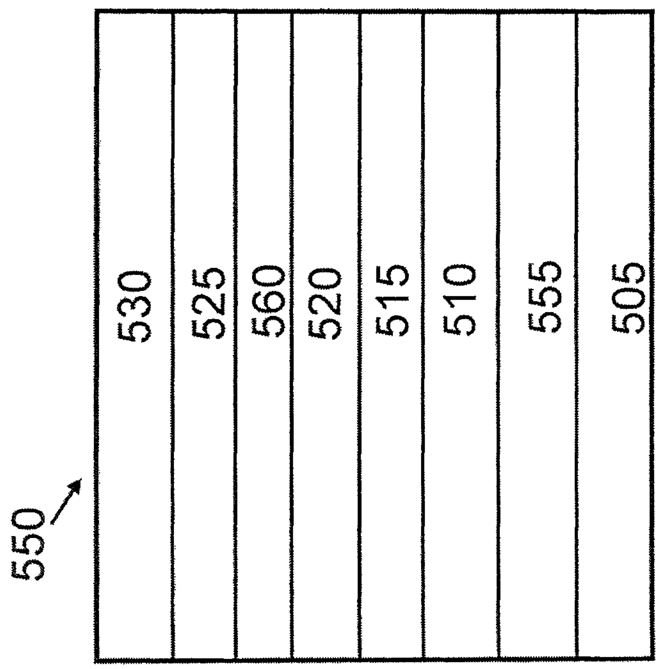


FIG. 5B

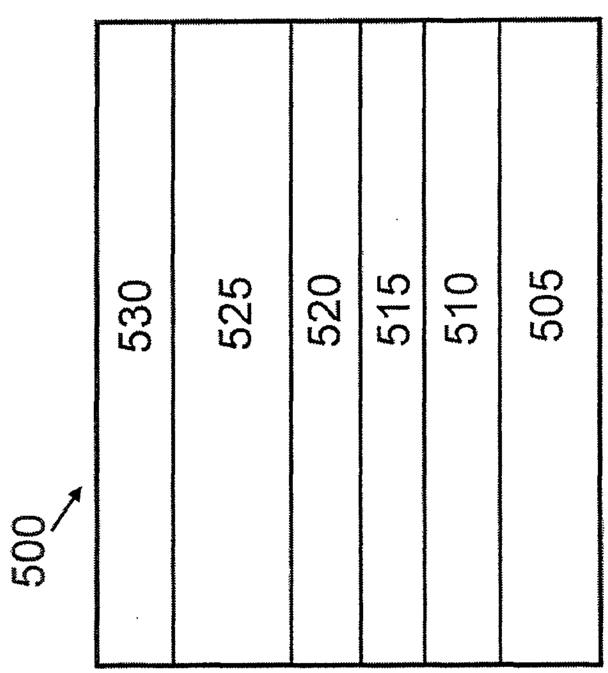


FIG. 5A

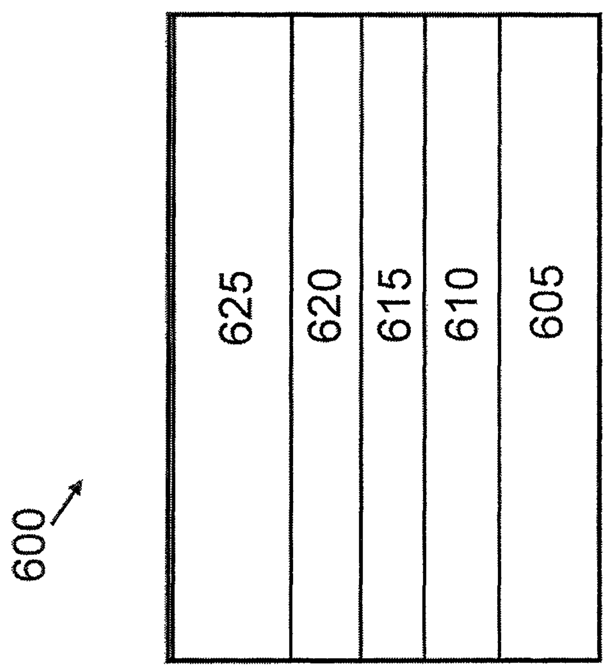


FIG. 6

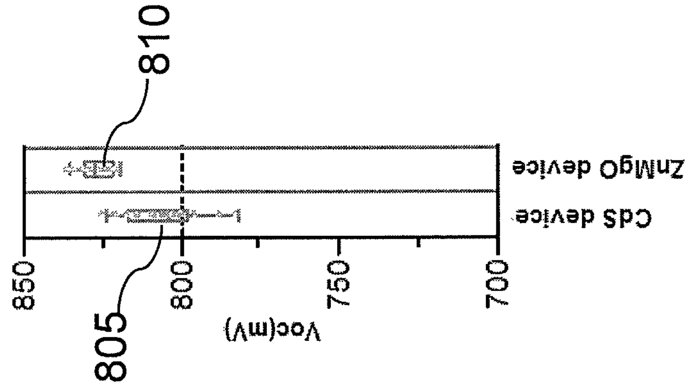

810
805
850
800
750
700
Voc(mV)
CdS device
ZnMgO device

FIG. 8A

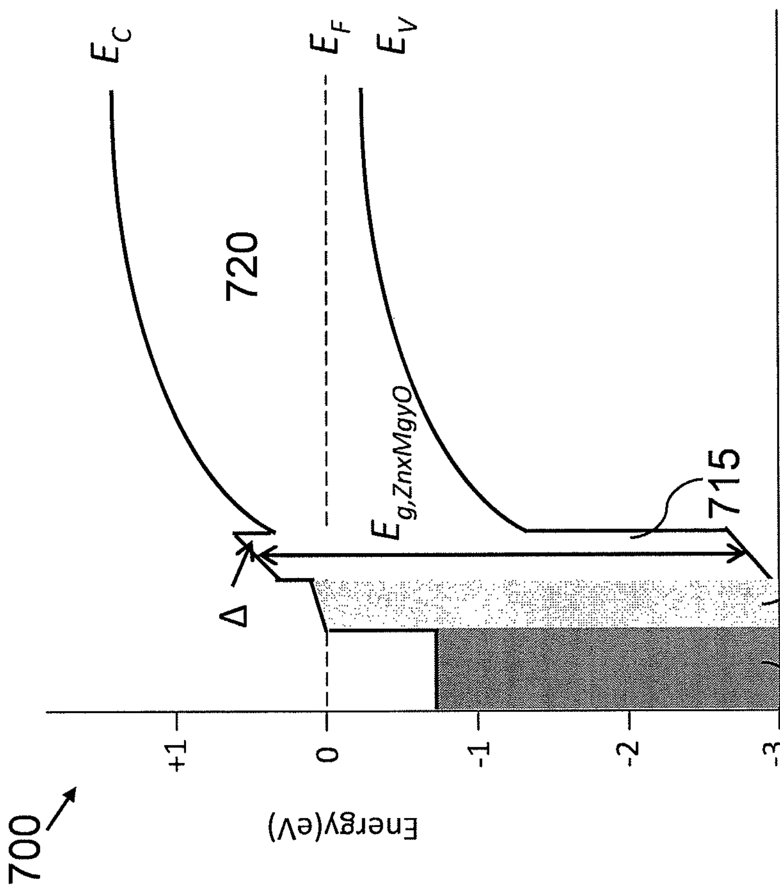
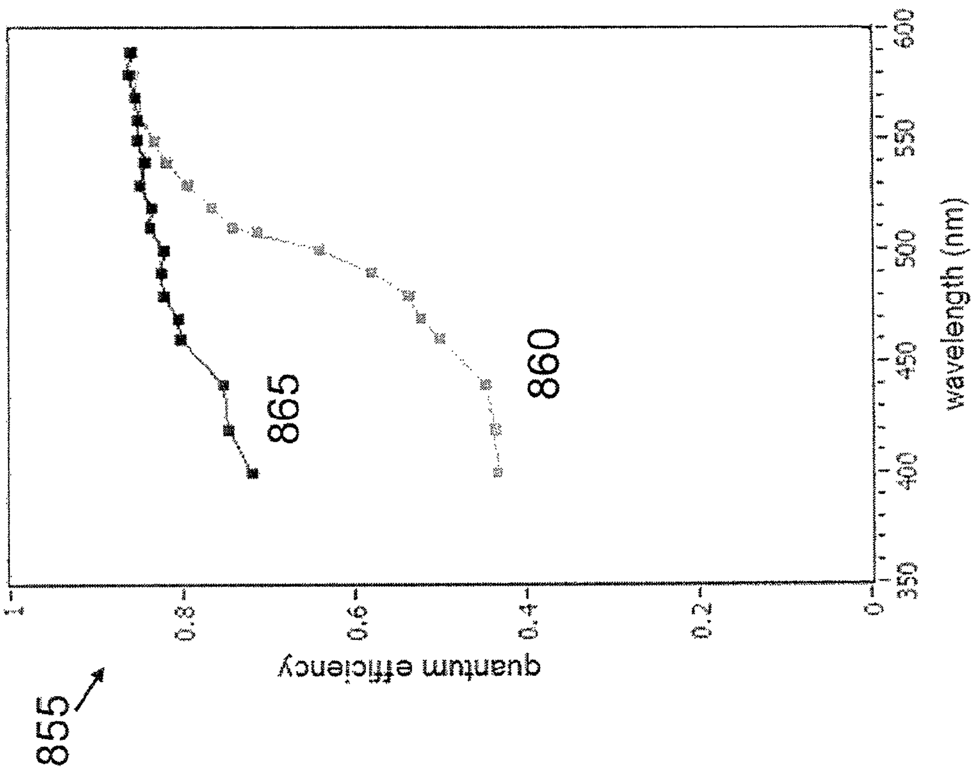

700
Energy(eV)
+1
0
-1
-2
-3
E_C
E_F
E_V
720
$E_{g,ZnxMgyO}$
Δ
715
710
705

FIG. 7



855
865
860
quantum efficiency
wavelength (nm)
0
0.2
0.4
0.6
0.8
1
350
400
450
500
550
600

FIG. 8B

PHOTOVOLTAIC DEVICE WITH A ZINC MAGNESIUM OXIDE WINDOW LAYER

CROSS REFERENCE TO RELATED APPLICATION

This application claims priority under 35 U.S.C. §119(e) to Provisional Application No. 61/385,399 filed on Sep. 22, 2010, which is hereby incorporated by reference in its entirety.

FIELD OF THE INVENTION

Embodiments of the invention relate to semiconductor devices and methods of manufacture, and more particularly to the field of photovoltaic (PV) devices.

BACKGROUND OF THE INVENTION

Photovoltaic devices generally comprise multiple layers of material deposited on a substrate, such as glass. FIG. **1** depicts a typical photovoltaic device. Photovoltaic device **100** may employ a glass substrate **105**, a transparent conductive oxide (TCO) layer **110** deposited on substrate **105**, a window layer **115** made from an n-type semiconductor material, an absorber layer **120** made from a semiconductor material, and a metal back contact **125**. Typical devices use cadmium telluride (CdTe) as absorber layer **120** and include glass substrate **105**, tin oxide (SnO_2) or cadmium tin oxide (Cd_2SnO_4) as TCO layer **110**, and cadmium sulfide (CdS) as the window layer **115**. By way of example, a deposition process for a typical photovoltaic device on substrate **105** may be ordered as TCO layer **110** including a n-type material doped with one of SnO_2 and Cd_2SnO_4, CdS window layer **115**, a CdTe absorber layer **120**, and metal back contact **125**. CdTe absorber layer **120** may be deposited on top of window layer **115**.

An exemplary energy band diagram of a typical thin-film photovoltaic device, such as a CdTe device is depicted in FIG. **2**. Band gap energy for F-doped SnO_2 as TCO layer is depicted as **205**, band gap energy of undoped SnO_2 as a buffer layer is depicted as **210**, band gap energy of CdS as the window layer is depicted as **215**, and band gap energy of CdTe as an absorber layer is depicted as **220**. Typically, the conduction band edge offset of CdS relative to CdTe, Δ, is usually −0.2 eV with an experimental uncertainty of +/−0.1 eV.

As depicted in FIG. **2**, Δ is the offset in the conduction band edge Ec between the window layer and absorber. In the case of a CdS/CdTe stack, Δ is about −0.2 eV. Theoretical modeling has shown that a more negative Δ leads to larger loss in Voc and FF due to increased rate at which photo carriers recombine at the window/absorber interface. When Δ is made slightly positive (0 to 0.4 eV), the recombination rate can be minimized, leading to improved Voc and FF.

CdS is the conventional window layer in many types of thin-film photovoltaic devices, including photovoltaic devices employing one of CdTe and Cu(In, Ga)Se_2 as an absorber layer. However, as depicted in FIG. **2**, the optical band gap for CdS is only 2.4 eV.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** depicts a typical photovoltaic device.

FIG. **2** depicts an exemplary energy band diagram of a typical thin-film photovoltaic device.

FIG. **3**A depicts a substrate structure according to one embodiment.

FIG. **3**B depicts a substrate structure according to another embodiment.

FIG. **4** depicts a substrate structure according to another embodiment.

FIG. **5**A depicts a thin-film photovoltaic device according to one embodiment.

FIG. **5**B depicts a thin-film photovoltaic device according to another embodiment.

FIG. **6** depicts a thin-film photovoltaic device according to another embodiment.

FIG. **7** depicts an energy band diagram of a thin-film photovoltaic device according to one embodiment.

FIG. **8**A depicts a graphical representation of open circuit voltage according to one embodiment.

FIG. **8**B depicts a graphical representation of quantum efficiency according to another embodiment.

DETAILED DESCRIPTION OF THE INVENTION

This disclosure is directed to photovoltaic devices and methods of production. In one embodiment, $Zn_{1-x}Mg_xO$ is employed for a window layer of substrate structure. FIG. **3** depicts substrate structure **300** according to one embodiment. Substrate structure **300** includes substrate **305**, transparent conductive oxide (TCO) layer **310**, buffer layer **315** and window layer **320**. TCO layer **310** may typically be employed to allow solar radiation to enter a photovoltaic device and may further act as an electrode. TCO layer **310** may include an n-type material doped with one of SnO_2 and Cd_2SnO_4. Window layer **320** may be employed to mitigate the internal loss of photo carriers (e.g., electrons and holes) in the device and may strongly influence device parameters including open circuit voltage (Voc), short circuit current (Isc) and fill factor (FF). In one embodiment, window layer **320** may allow incident light to pass to an absorber material to absorb light. According to one embodiment, to improve overall photo emission efficiency of window layer **320**, window layer **320** comprises a $Zn_{1-x}Mg_xO$ compound.

In one embodiment, substrate structure **300** may include a glass substrate **305**, and TCO layer **310**. Buffer layer **315** may be optional. Window layer **320** (e.g., $Zn_{1-x}Mg_xO$ layer) may be directly on top of TCO layer **310**, the TCO layer including one or more of a F-doped SnO_2, undoped SnO_2, and Cd_2SnO_4. When TCO layer **310** includes an undoped Cd_2SnO_4, the TCO layer has no extrinsic dopant, however the layer may be highly n-type due to oxygen vacancies.

According to another embodiment, substrate structure **300** may be provided for manufacturing photovoltaic devices. As depicted in FIG. **3**A, the substrate structure includes substrate **305**, TCO layer **310**, low conductivity buffer layer **315**, and $Zn_{1-x}Mg_xO$ window layer **320**. The substrate structure of FIG. **3**A includes $Zn_{1-x}Mg_xO$ window layer **320** onto which other layers of a device can be deposited (e.g., absorber layer, metal back, etc.). In one embodiment, $Zn_{1-x}Mg_xO$ window layer **320** may be deposited onto a F—SnO_2 based substrate structure (like TEC10). Similarly, substrate structure **300** can be a cadmium stannate (CdSt) substrate structure. Buffer layer **315** may be used to decrease the likelihood of irregularities occurring during the formation of the semiconductor window layer. Buffer layer **315** may be made from a material less conductive than TCO layer **310**, such as undoped tin oxide, zinc tin oxide, cadmium zinc oxide or other transparent conductive oxide or a combination thereof In certain embodiments, substrate structure **300** may not include a buffer layer as depicted in FIG. **4**. When substrate structure **300** includes a low conductivity buffer layer **315**, the buffer layer is arranged between the substrate **305** (e.g., glass) and the $Zn_{1-x}Mg_xO$ window layer.

In one embodiment the thickness of $Zn_{1-x}Mg_xO$ window layer **320** ranges from 2 to 2000 nm. In another embodiment, the composition of x in $Zn_{1-x}Mg_xO$ is greater than 0 and less than 1. Window layer **320** may be a more conductive material relative to conventional window layer materials, such as CdS. Additionally, window layer **320** may include a window layer material that allows for greatly reduced fill factor (FF) loss in a blue light deficient environment. A $Zn_{1-x}Mg_xO$ window layer may allow for more solar radiation in the blue region (e.g., 400 to 475 nm) that can reach the absorber leading to higher short circuit current (Isc).

In an alternative embodiment, a photovoltaic device, such as substrate structure **300** may include a $Zn_{1-x}Mg_xO$ compound material as window layer **320** and one or more of a barrier layer and a CdS window layer, as depicted in FIG. **3**B. Barrier layer **355** of substrate structure **350** can be silicon oxide, silicon aluminum oxide, tin oxide, or other suitable material or a combination thereof CdS window layer **360** may be deposited on $Zn_{1-x}Mg_xO$ layer **320**, wherein the CdS window relates to a surface for depositing an absorber layer. In one embodiment, a photovoltaic device includes a $Zn_{1-x}Mg_xO$ window layer, in addition to a substrate structure (e.g., substrate structure **300**). For example, substrate structure **300** may utilize a TCO stack including a substrate **305**, TCO layer **310** and one or more additional elements. In another embodiment, substrate structure **300** may include buffer layer **315**.

$Zn_{1-x}Mg_xO$ may be advantageous over a conventional CdS window layers as $Zn_{1-x}Mg_xO$ has a wider band gap relative to a device having a CdS window layer. As such, more solar radiation can reach a CdTe absorber, which leads to higher Isc. Similarly, an improved conduction band edge alignment can be achieved by adjusting composition of $Zn_{1-x}Mg_xO$, which leads to higher Voc. The dopant concentration can be in the range of 10^{15} to 10^{19} atoms (or ions) of dopant per cm^3 of metal oxide. Carrier density of $Zn_{1-x}Mg_xO$ can be greater than the carrier density of CdS. As such, a stronger n-p semiconductor heterojunction can be formed increasing the built-in potential of the solar cells and minimizing recombination at the interface. A more conductive window layer can also improve the loss in fill factor in a low light environment (e.g., photoconductivity effect), where the percentage of blue light is reduced greatly as compared to under full sun light.

Referring to FIG. **4**, the substrate structure of FIG. **3**A is depicted according to another embodiment. Substrate structure **400** includes substrate **405**, TCO layer **410**, and $Zn_{1-x}Mg_xO$ window layer **420**. Substrate structure **400** may be manufactured at lower cost in comparison to the substrate structure of FIG. **3**A

According to another embodiment, $Zn_{1-x}Mg_xO$ may be employed for a window layer of a photovoltaic device. FIGS. **5**A-**5**B depict photovoltaic devices according to one or more embodiments, which may be formed as thin-film photovoltaic devices. Referring first to FIG. **5**A, photovoltaic device **500** includes substrate **505**, transparent conductive oxide (TCO) layer **510**, buffer layer **515**, window layer **520**, absorber layer **525**, and metal back contact **530**. Absorber layer **525** may be employed to generate photo carriers upon absorption of solar radiation. Metal back contact **530** may be employed to act as an electrode. Metal back contact **530** may be made of molybdenum, aluminum, copper, or any other high conductive materials. Window layer **520** of photovoltaic device **500** may include a $Zn_{1-x}Mg_xO$ compound.

More specifically, photovoltaic device **500** may include one or more of glass substrate **505**, TCO layer **510** made from SnO_2 or Cd_2SnO_4, buffer layer **515**, a $Zn_{1-x}Mg_xO$ window layer **520**, a CdTe absorber **525**, and a metal back contact **530**. Buffer layer **515** may relate to a low conductivity buffer layer, such as undoped SnO_2. Buffer layer **515** may be used to decrease the likelihood of irregularities occurring during the formation of the semiconductor window layer. Absorber layer **525** may be a CdTe layer. The layer thickness and materials are not limited by the thicknesses depicted in FIGS. **5**A-**5**B. In one embodiment, the device of FIG. **5**A may employ the substrate of FIG. **3**A. In certain embodiments, photovoltaic device **500** may or may not include a low conductivity buffer layer **515**, absorber layer **520** a metal back contact **530**.

Photovoltaic device **500** may include one or more of a cadmium telluride (CdTe), copper indium gallium (di)selenide (CIGS), and amorphous silicon (Si) as the absorber layer **525**. In one embodiment, a photovoltaic device may be provided that includes a $Zn_{1-x}Mg_xO$ window layer **520** between a substrate structure, which may or may not include a low conductivity buffer layer **515**, and the absorber layer **525**. In certain embodiments, the device may additionally include a CdS window layer in addition to $Zn_{1-x}Mg_xO$ window layer **520**.

In an alternative embodiment, photovoltaic device **500** may include a $Zn_{1-x}Mg_xO$ compound material as window layer **520** and one or more of a barrier layer and a CdS window layer as depicted in FIG. **5**B. Barrier layer **555** can be silicon oxide, silicon aluminum oxide, tin oxide, or other suitable material or a combination thereof. CdS window layer **560** may be deposited on $MS_{1-x}O_x$ layer **520**, wherein CdS window layer **560** provides a surface for depositing an absorber layer.

In certain embodiments, photovoltaic device **500** may not include a buffer layer. FIG. **6** depicts thin-film photovoltaic device **600** which includes glass substrate **605**, TCO layer **610** made from SnO_2 or Cd_2SnO_4, a $MS_{1-x}O_x$ window layer **615**, a CdTe absorber **620**, and a metal back contact **625**

FIG. **7** depicts the band structure of a photovoltaic device, such as a photovoltaic device that employs a CdTe absorber layer, according to one embodiment. In FIG. **7**, Band gap energy depicted for F-doped SnO_2 as a TCO layer is depicted as **705**, undoped SnO_2 as a buffer layer is depicted as **710**, $Zn_{1-x}Mg_xO$ as the window layer depicted as **715**, and CdTe as the absorber layer is depicted as **720**. As further depicted, the conduction band edge offset of $Zn_{1-x}Mg_xO$ relative to CdTe, Δ, can be adjusted to 0-0.4 eV. Another advantage of the photovoltaic device of FIG. **3** may be a wider band gap in comparison to CdS.

Both zinc oxide (ZnO) and magnesium oxide (MgO) are wide band gap oxides. ZnO has a band gap of 3.2 eV and MgO has a band gap of about 7.7 eV. ZnO may further be advantageous as it is highly dopable. The ternary compound $Zn_{1-x}Mg_xO$ should have a band gap of at least 3 eV as predicted by simulation, which is much larger than that of CdS, and is thus more transparent to blue light. On the other hand, ZnO has a Δ from −0.6 to −1.0 eV relative to CdTe conduction band edge, while MgO has a positive Δ about 2.7 eV. Therefore, the composition of the ternary compound $Zn_{1-x}Mg_xO$ can be tuned to lead to a Δ that is slightly positive, as shown in FIG. **4**.

FIGS. **8**A-**8**B depict advantages that may be provided by employing $Zn_{1-x}Mg_xO$ in the window layer of a photovoltaic device. Referring first to FIG. **8**A, a graphical representation is shown of open circuit voltage for a CdS device **805** and $Zn_{1-x}Mg_xO$ device **810**.

The improvement in device Voc by replacing a CdS window layer with a $Zn_{1-x}Mg_xO$ window layer may include improved open circuit voltage from 810 mV to 826 mV. FIG.

8B depicts a graphical representation of quantum efficiency **855** in the range of 400 to 600 nm. As depicted in FIG. **8**B, a CdTe device with $Zn_{1-x}Mg_xO$ window layer, depicted as **865**, has a higher quantum efficiency relative to a CdS window layer, depicted as **860**, from 400-500 nm. The current density of $Zn_{1-x}Mg_xO$ may relate to 22.6 mA/cm^2 relative to 21.8 mA/cm^2 for CdS. The values of Voc improvements described herein are exemplary, as it may be difficult to measure a certain improvement delta. Source current may improve up to 2 mA/cm^2, wherein the improvement compared to a CdS devices may depend on the thickness of CdS employed.

In another aspect, a process is provided for manufacturing photovoltaic devices and substrates to include a $Zn_{1-x}Mg_xO$ window layer as depicted in FIGS. **3**A and **3**B. Substrate structure **300**, containing a $Zn_{1-x}Mg_xO$ window layer, may be manufactured by one or more processes, wherein one or more layers of the structure may be manufactured by one or more of sputtering, evaporation deposition, and chemical vapor deposition (CVD). Similarly, the $Zn_{1-x}Mg_xO$ window layer of photovoltaic device **300** may be manufactured by one or more the following processes, including sputtering, evaporation deposition, CVD, chemical bath deposition and vapor transport deposition.

In one embodiment, a process for manufacturing a photovoltaic device may include a sputtering process of a $Zn_{1-x}Mg_xO$ window layer by one of DC Pulsed sputtering, RF sputtering, AC sputtering, and other manufacturing processes in general. The source materials used for sputtering can be one or more ceramic targets of a $Zn_{1-x}Mg_xO$ ternary compound, where x is in the range of 0 to 1. In one embodiment, source materials used for sputtering can be one or more targets of $Zn_{1-x}Mg_x$ alloy, where x is in the range of 0 to 1. In another embodiment, source materials used for sputtering can be two or more ceramic targets with one or more made from ZnO and the one or more made from MgO. In another embodiment, source materials used for sputtering can be two or more metal targets with one or more made from Zn and one or more made from Mg. Process gas for sputtering the $Zn_{1-x}Mg_xO$ can be a mixture of argon and oxygen using different mixing ratios.

In one embodiment, a $Zn_{1-x}Mg_xO$ window layer can be deposited by atmospheric pressure chemical vapor deposition (APCVD) with precursors including but not limited to diethyl zinc, bis(cyclopentadienyl)magnesium with reagent such as H_2O or ozone.

According to another embodiment, the process for manufacturing a photovoltaic device may result in a conduction band offset with respect to an absorber layer. For example, the conduction band offset of a window ($Zn_{1-x}Mg_xO$) layer with respect to the absorber layer can be adjusted between 0 and +0.4 eV by choosing the proper value of x. Further, the conductivity of a $Zn_{1-x}Mg_xO$ window layer can be adjusted within a range of 1 mOhm per cm to 10 Ohm per cm by doping the zinc magnesium oxide with one of aluminum (Al), manganese (Mn), niobium (Nb), nitrogen (N), fluorine (F), and by introduction of oxygen vacancies. In one embodiment the dopant concentration is from about 1×10^{14} cm^{-3} to about 1×10^{19} cm^{-3}. In one embodiment, the window layer is formed using a sputter target having a dopant concentration from about 1×10^{17} cm^{-3} to about 1×10^{18} cm^{-3}.

What is claimed is:

1. A photovoltaic device comprising:

a glass substrate;

a barrier layer over the substrate;

a transparent conductive oxide layer over the barrier layer;

a buffer layer over the transparent conductive oxide layer;

a first semiconductor window layer over the buffer layer, the first semiconductor window layer comprising $Zn_{1-x}Mg_xO$, wherein $0<x<1$;

a second semiconductor window layer comprising cadmium sulfide over the first semiconductor window layer; and

a cadmium telluride semiconductor absorber layer over the second semiconductor window layer;

wherein the conduction band offset of the first semiconductor window layer with respect to the cadmium telluride semiconductor absorber layer is in the range of 0 to +0.4 eV.

2. The photovoltaic device of claim **1**, wherein the first semiconductor window layer is on the buffer layer.

3. The photovoltaic device of claim **1**, wherein the thickness of the first semiconductor window layer ranges from about 2 nm to about 2000 nm.

4. The photovoltaic device of claim **2**, wherein the conductivity of the first semiconductor window layer is within a range of about 1 mOhm per cm to about 10 Ohm per cm.

5. The photovoltaic device of claim **2**, wherein the first semiconductor window layer is doped with Al, Mn, Nb, N, F or by introducing oxygen vacancies.

6. The photovoltaic device of claim **2**, wherein:

the barrier layer is between the glass substrate and the transparent conductive oxide layer.

7. The photovoltaic device of claim **1**, wherein the first semiconductor window layer is doped with Al, Mn, Nb, N, F or by introducing oxygen vacancies.

8. The photovoltaic device of claim **1**, wherein the first semiconductor window layer has a dopant concentration of between about 1×10^{14} cm^{-3} and about 1×10^{19} cm^{-3}.

9. The photovoltaic device of claim **8**, wherein the first semiconductor window layer has a dopant concentration of between about 1×10^{17} cm^{-3} and about 1×10^{18} cm^{-3}.

* * * * *